Lecture notes

*ZDA – 04 – automotive (in vehicle) detectors*

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# Introduction

Lecture notes for course ZDA, taken from the internet resources like IEEE Xplore ([ieeexplore.ieee.org](file:///Z:\PB\vyuka\ZDA\lecture_notes\01_history\ieeexplore.ieee.org\)), Google news ([news.google.com](file:///Z:\PB\vyuka\ZDA\lecture_notes\01_history\news.google.com)), Google books ([books.google.com](http://books.google.com/)) and others ([http//www.cvel.clemson.edu/auto/sensors/auto-sensors.html](http://www.cvel.clemson.edu/auto/sensors/auto-sensors.html)). The text itself should be taken as a basic knowledge that students are required to have to get through the first lecture.

## Structure

This (fourth) part deals with description of automotive detectors. For each detector type, this text shall cover architecture, construction, implementation and maintenance of the sensor as well functionality and use within vehicular systems.

# Automotive sensors history

According to (Fleming, 2001) sensors are essential components of automotive electronic control systems. Sensors are defined as “*devices that transform (or transduce) physical quantities such as pressure or acceleration (called measurands) into output signals (usually electrical) that serve as inputs for control systems.*” Primarily the automotive sensors were discrete devices used to measure oil pressure, fuel level, coolant temperature, etc. Starting in the late 1970s, microprocessor-based automotive engine control modules were phased in to satisfy federal emissions regulations. These systems required new sensors such as MAP (manifold absolute pressure), air temperature, and exhaust-gas stoichiometric air-fuel-ratio operating point sensors. The need for sensors is evolving and is progressively growing. For example, in engine control applications, the number of sensors used will increase from approximately ten in 1995, to more than thirty in 2010.

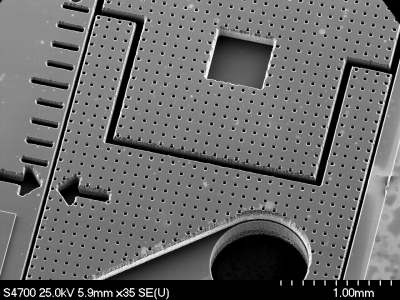


Figure 1. MicroElectroMechanical Systems sensor (source

[www.memsnet.org](http://www.memsnet.org))

Important automotive sensor technology are MicroElectroMechanical Systems (MEMS). Manufacturing began in 1981 with pressure sensors for engine control, continued in the early 1990s with accelerometers to detect crash events for air bag safety systems and in recent years has further developed with angular-rate inertial sensors for vehicle-stability chassis systems. MEMS brings together silicon-based microelectronics with micromachining technology, making possible the realization of complete **systems-on-a-chip**. It utilizes the economy of batch processing, together with miniaturization and integration of on-chip electronic intelligence.

Automotive environmental operating requirements are very severe, with temperatures of -40 to +125 C (engine compartment), vibration sweeps up to 10 g for 30 h, drops onto concrete floor (to simulate assembly mishaps), electromagnetic interference and compatibility, and so on. Cost is also always a major concern. Mature sensors (e.g., pressure types) are currently sold in large-quantities (greater than one million units annually) at a low cost of less than $3 (US) per sensor, whereas more complex sensors (e.g., exhaust gas oxygen, true mass intake air flow and angular rate) are generally several times more costly. Automotive sensors must, therefore, satisfy a difficult balance between accuracy, robustness, manufacturability, interchangeability, and low cost.

# Automotive sensor classification

The three major areas of systems application for automotive sensors are powertrain, chassis, and body (Fig 2). In the present systems-classification scheme, anything that isn’t powertrain or chassis is included as a body systems application.

Powertrain applications for sensors, can be thought of as the “1stWave” of increased use of automotive sensors because they led the first widespread introduction of electronic sensors. Chassis applications for sensors are considered to be the “2nd Wave” of increased use of sensors, and body applications are called the “3rd Wave.”

Certain types of sensors predominate in powertrain application, namely rotational motion sensors, pressure, and temperature. New types of recently introduced (Fleming, 2001) powertrain sensors, include the cylinder pressure, pedal/accelerator rotary position, and oil quality sensors.

Certain types of sensors also predominate in chassis applications, namely rotational motion and pressure. But, instead of temperature, there are inertial acceleration and angular-rate sensors. New types of sensors, currently found in chassis systems applications, include the yaw angular rate, steering wheel angular position, and strut-displacement position sensors.

Body sensors are very diverse and no specific types of sensors are dominant. They range from crash-sensing accelerometers, to ultrasonic near-obstacle sensors, to infrared thermal imaging, to millimeter-wave radar, to ambient-air electrochemical gas sensors. Once again, new types of sensors, currently found in body systems applications, include the ultrasonic-array reversing aid, lateral lane-departure warning, and infrared-thermal imaging night-vision sensors.





Figure 2 Simplified diagrams of Powertrain, Chassis and body systems, control functions and applications

# Rotational sensors

Rotational motion sensors measure shaft rotational motion (they also detect reference points such as those created by the absence of one tone-wheel tooth). According to (Fleming, 2001) rotational motion sensors have in the USA the most unit sales and also the highest dollar sales, which makes them number one in the present categorization scheme.

## Variable Reluctance

These sensors, also called inductive types, are electromagnetic devices which produce a pulsetrain- like voltage-output signal governed by the time-varying fluctuations of magnetic flux created by rotating motion of mechanical parts. As gear teeth, slots, or magnetized poles, rotate with a shaft and pass by a sensor; flux variations are generated in the sensor’s magnetic circuit (which includes a bias magnet). Via Faraday’s law, the sensor generates voltage variations in its sensing coil which correspond to the derivative of magnetic flux with respect to time. The output of a reluctance style tachometer is a sine wave.

Reluctance tachometers do not require a power supply, so their base cost is low. However, the unamplified sine wave signal is not as strong as "zero-speed" or "square wave" style encoders. Also reluctance tachometers do not sense speed at low RPM. Typically, their output does not reach an acceptable level until the speed reaches 30-50 rpm.

Variable reluctance sensors feature low cost, small-to-moderate size, self-generated signals, and good temperature stability. On the other hand, disadvantages include loss of signal at zero speed, variable signal strength and signal phase which are dependent on shaft speed (which typically limit rotational measurement repeatability to about 0.1 degree), and operation generally limited to sensor air gaps no greater than about 2 mm.

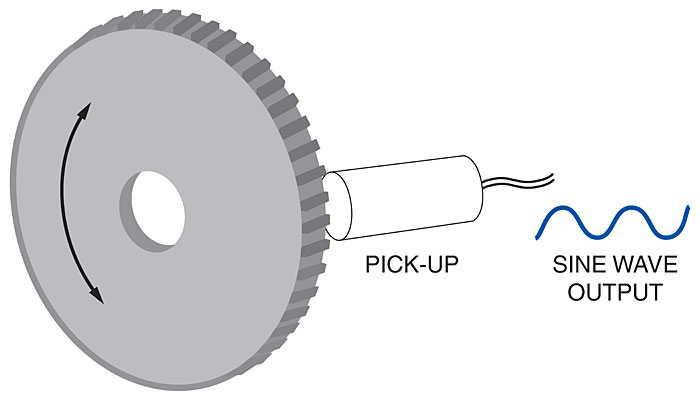


Figure 3 Schema of variable reluctance rotational type sensor (source

[www.avtron.com](http://www.avtron.com))

## Wiegand Effect

Wiegand effect sensors are based on the interaction of an applied magnetic field with a sensing element that consists of a magnetic-alloy wire having a radial-gradient magnetization that varies from the wire’s core to its periphery. When the strength of the field in the magnetic-circuit of the sensor exceeds a threshold value, the magnetization state in the Wiegand wire element rapidly switches polarity, thereby self-generating a voltage pulse, detected by a pickup coil. Wiegand sensors feature

self-generated signal and a high-level voltage-pulse signal (at low rotation speeds). Disadvantages include spike like-signal output and high-volume manufacturability cost issues. For more information see (Dlugos, 1998).

## Hall Effect

Hall sensors produce a voltage signal that corresponds one-to-one with the fluctuations of magnetic flux created by rotating motion of mechanical parts. As tone-wheel gear teeth rotate past a Hall sensor (and its integral bias-magnet); magnetic flux variations are generated similar to those for the variable reluctance sensor, but instead of detecting the time-derivative of flux, the Hall sensor detects the flux level itself.



Figure 4 Hall effect rotation sensor (source

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Hall sensors are semiconductor active devices and therefore require a bias current. The Hall voltage output signal is linearly proportional to the transverse component of the flux density passing through the sensing element. In order to (a) cancel out the common-mode dc voltage component associated with the average flux level and (b) to double the output signal, pairs of Hall elements are mounted in a differential mode, side-by-side, and parallel to the direction of tooth travel. For effective differential operation, spacing between sensing elements is matched to the pitch between tone-wheel teeth.

Hall sensors are made using bipolar semiconductor technology which allows their fabrication directly on the same chip along with microelectronic signal-processing circuitry. Functions such as amplification, temperature compensation, signal conditioning, etc., can be economically added. Hall sensors feature low cost, small size, operation to zero speed, excellent linearity, and rotational measurement repeatability in the neighborhood of 0.05 . On the other hand, disadvantages include maximum operating temperature of about 175 °C, air gap operation limited to no greater than about 2.5 mm, and sensitivity to external pressure acting on the sensor package.

## Magnetoresistor

Magnetoresistor devices exhibit a change of resistance, proportional to magnetic flux density. The resistance change is based on Lorentz force, where geometric patterns of narrow, uniformly spaced, conductive shorting stripes are deposited, perpendicular to current flow direction, on thin layers of high-carrier-mobility semiconductors (InSb or InAs). As current flows in the presence of an orthogonal external magnetic field, Hall-fields and internal shorting by the conductive stripes cause the conduction current to follow more tortuous (more zig-zag), higher-resistance, paths; thereby creating a resistive output signal. Simply put these sensors use resistors that are sensitive to magnetic fields. When a rotor with magnetic poles is sensed, a sine wave is generated which is then converted to a square wave.

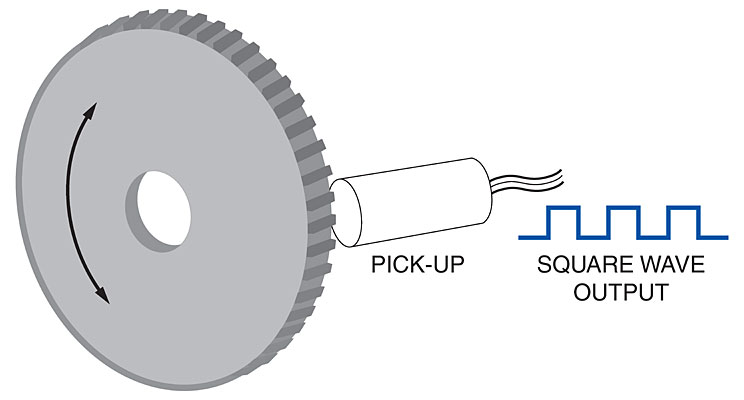


Figure 5 Schema of Magnetoresistive rotational type sensor (source [www.avtron.com](http://www.avtron.com))

Magnetoresistor sensors are likewise amenable to fabrication of microelectronic signal-processing integrated circuitry directly on the same chip with the sensing element. The sensor features operation to zero speed, rotation-direction sense, excellent rotational-measurement repeatability in the neighborhood of 0,025, air gap operation up to 3 mm and outstanding temperature stability (maximum operating temperature of 200 ˚C). Disadvantages include medium size, medium cost, and the active-device bias current requirement.

## AMR Magnetoresistive

AMR sensors are well suited to measuring both linear and angular position and displacement in the Earth's magnetic field. These devices are made of a nickel-iron (Permalloy) thin film deposited on a silicon wafer and patterned as a resistive strip.

The film's properties cause it to change resistance by 2%-3% in the presence of a magnetic field. In a typical configuration, four of these resistors are connected in a Wheatstone bridge to permit measurement of both field magnitude and direction along a single axis. The bandwidth is usually in the 1-5 MHz range. The reaction of the magnetoresistive effect is very fast and not limited by coils or oscillating frequencies.

AMR sensors are also amenable to fabrication of integrated circuitry directly on the same chip. The sensor similarly features operation to zero speed, rotation-direction sense, excellent rotational-measurement repeatability, air gap operation up to 3 mm, and maximum operating temperature of 200˚C. Disadvantages include medium size (?), medium cost, and the active-device bias current requirement.

## GMR Magnetoresistive

GMR giant magnetoresistive sensors utilize ferromagnetic/nonmagnetic layered structures made up of atomically thin films, in the range of 2-to-5-nm thickness. The GMR effect is quantum mechanical in nature. The reason GMR sensors are called “giant” is because (at very low temperatures) they exhibit sensitivities to variations of applied magnetic field which are up to 20 times greater than those for AMR sensors. At room temperature, the GMR sensitivity advantage diminishes, but is still three to six times greater than that for AMR sensors.

Although GMR and AMR sensors have different operating mechanisms, the two sensors function similarly; i.e., both respond primarily to field orientation/direction rather than to field strength. GMR sensors again are amenable to fabrication of integrated circuitry directly on the same chip. The sensor similarly features operation to zero speed, rotation direction sense, excellent rotational-measurement repeatability, extended air gap operation up to 3.5 mm, and a maximum operating temperature of 150 C. Disadvantages likewise include

medium size, medium cost, the active-device bias current requirement, and need for tightly controlled limits on its bias point.

## Photoelectric/optical

This system uses an infrared LED light source that shines through a rotating, slotted or photo-etched disk, and on to a photoelectric cell. When the slots align with the LED, light shines through to give a high output from the sensor. When they misalign, the output goes low. The signal generated is amplified and produces a square wave output.

This design allows very high speed operation (up to 32768 pulses per rotation) and is also sensitive for down to zero speed. They require an external or drive power supply.

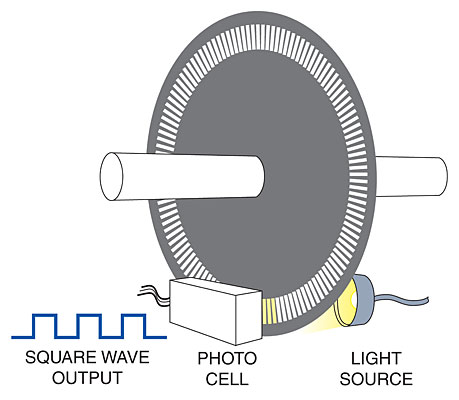


Figure 6 Schema of Photoelectric rotational type sensor (source [www.avtron.com](http://www.avtron.com))

## Automotive Applications

Major uses for variable reluctance sensors include engine crankshaft and camshaft rotational control of spark timing, fuel injection timing and engine speed measurement, and for control of transmission input and output shaft speeds for electronically controlled gear shifting. Another major application for variable reluctance sensors is wheel speed, on all four wheels (for the ABS antilock brake system, traction control and vehicle stability).

Wiegand effect sensors find application in aftermarket high-performance ignition systems. More stringent, OBD onboard diagnostic engine misfire detection requirements, newly enacted by California and federal regulators, have necessitated higher-accuracy crankshaft angular-measurements to detect the absence of individual cylinder firing torques (i.e., misfire) and this has spurred the introduction of the higher-performance magnetoresistor, AMR and GMR types of sensors. Another important application for higher-performance sensors which operate to zero speed, is the measurement of wheel rotation in vehicle navigation systems.

# Pressure Sensors

Pressure sensors have some very diverse automotive applications. They measure pressures ranging from 10 kPa-vacuum (for OBD evaporative fuel leak detection), to 180 MPa (for diesel common-rail fuel pressure systems). This is a 18 000

1 variation in full-scale pressure range measurement requirements! Therefore there exist several different pressure sensor technologies.

Pressure sensors have the second greatest unit sales and the sixth highest gross sales revenue, which makes them number two in the present categorization scheme.

## Piezoresistive Micromachined

Pressure sensing elements are batch fabricated, a thousand or more per wafer, using a “bond and etchback” process. Silicon diaphragms are micromachined using electrochemical etching and a silicon-to-silicon bonding process forms a vacuum reference chamber [16]. Over the past two decades, sensor die sizes have shrunk and wafer diameters have increased—both factors have helped to lower the cost of micromachined pressure sensors—see [5] page 1752. Piezoresistive strain-sense elements are implanted in appropriate areas of an etched silicon diaphragm where strains are most sensitive to applied pressure. The strain-sense elements are electrically connected into a Wheatstone bridge circuit, thereby providing a means of detecting pressure acting on the diaphragm. Modern sensors feature on-chip digital electronics which provide signal conditioning, programmable calibration of span and offset, built-in compensation for nonlinearity and temperature effects, ratiometric output signal, high accuracy over a wide temperature range and nearly identical part-to-part interchangeability. 2)

## Capacitive Touch-Mode Micromachined

In applications where zero-pressure range measurement is not required and where low power consumption is an advantage; capacitive “touch-mode” micromachined pressure sensors are used. In this case an extended, more flexible, silicon diaphragm is fabricated. Increasing pressure, acting on the outside surface of the flexible diaphragm, progressively deflects the diaphragm downwards, progressively flattening it against a dielectric/insulating layer deposited above a base electrode. This geometric, progressive, flattening produces a linear increase in capacitance which is insensitive to the interfering effects of temperature [17]. 3)

## Capacitive Ceramic-Module

In very harsh automotive applications—such as hydraulic fluids (brake, power steering, suspension, etc.)—capacitive ceramic-module configurations, also called capsules, are utilized [18]. This sensor basically consists of a diaphragm and a much thicker substrate which has a shallow cavity aligned under the diaphragm. Adjacent surfaces of the diaphragm and substrate are electroded using a guard ring geometry (which eliminates the influence of stray capacitance). The two pieces are bonded together to form a vacuum reference chamber. Increased hydraulic pressure, acting on the outside surface of the diaphragm, deflects the diaphragm closer to the underlying substrate and this produces an increase in capacitance. To insure EMI noise immunity, a high-level, binary, pulse-width-modulated output signal is provided by custom IC electronics, integrally built into the sensor package. [It’s noted that this is possible with any capacitive sensor]. 4)

## Piezoresistive Polysilicon-on-Steel

When extreme high pressure is measured—such as diesel-engine common-rail fuel pressure (up to 180-MPa)—polysilicon-on-steel sensor configurations are utilized [19]. A stainless-steel cylinder, has a closed end which is thinned down to create a stiff diaphragm. Increased hydraulic pressure, acting on the inside surface of the diaphragm, deflects the diaphragm. Polysilicon pressure-sensing elements are vapor deposited on the outside (protected side) of the steel diaphragm. Strain sensing elements are electrically connected in a Wheatstone bridge circuit, thereby providing a means of detecting pressure acting on the diaphragm.

## Automotive Applications

Piezoresistive micromachined sensors are extensively used to measure engine manifold pressure (absolute and barometric), turbo-boost pressure, and evaporative fuel leak pressure. Capacitive touch-mode micromachined sensors are used to measure tire pressure inside the rotating wheel and engine oil pressure (two applications where accurate indication of the zero point isn’t required). Capacitive ceramic-module sensors, are used to measure brake fluid pressure (for cruise control disengagement and ABS braking regulation), suspension hydraulic pressure, and A/C compressor pressure. Piezoresistive polysilicon-on-steel sensors are used to measure common-rail FI (fuel injection) pressure, and vehicle suspension dynamic-control hydraulic pressure.

# Angular and Linear Position Sensors

Position sensors measure linear displacements ranging from less than one micron (a typical full-scale sensing-element movement inside a MEMS sensor) to over 200 mm (the stroke/travel of a strut in an active suspension system). This is a 200 000

1 variation in full-scale displacement range. An example of an angular- position application is the measurement over four complete revolutions, with a 1-degree measurement accuracy requirement, of steering-wheel angular position. Position sensors have the third greatest unit sales and the third highest gross sales revenue, which makes them number three in the present categorization scheme.

## Potentiometric

Potentiometric sensors utilize the property that the resistance of an appropriately made film, or screenprinted track, varies linearly with length. The wiper(s) can be either linearly or angularly displaced by the part whose position is to measured. The use of multiple, redundant, wipers and tracks provides improved sensor reliability [20], [21]. 2)

## Hall Effect

In an appropriate magnetic circuit, Hall sensor voltage varies as ; where is the angle between flux density acting on the sensor and bias current applied to the sensor. Typically, two Hall sensing elements are mounted in quadrature (geometrically oriented 90 from each other). The two Hall elements each provide output signals; one varying as “ ,” and the other as “ 2 ”. The output signal is derived from the inverse tangent of “ ,” the ratio of the quadrature element signals. This provides a linear indication of the angular position of the magnet creating field (attached to the shaft), thereby determining the angular position of the shaft [22]. Hall sensors are also used for linear position measurements, where magnet “head-on” and “slide-by” movements detect linear position—see [13, pages 99–103]. 3)

## AMR Anisotropic Magnetoresistive

This sensor was previously described in part 5 of Section A. The sensor exhibits changes of resistance as an external magnetic field rotates with respect to its sensing-elements. Two sets of four sensing elements are typically used, each set is physically mounted (i.e., mechanically) offset from each other by a 45 angle. This 45 offset again produces a quadrature 90 electrical phase angle difference. The two sets of sensing elements are connected in Wheatstone bridge signal-detection IC circuits. Both bridge circuits respond to the orientation of the external magnetic field (not its field strength). In a manner akin to the Hall sensor, output signals from the two AMR-sensor bridge circuits are obtained; but in this case, the signals vary as, “ 2 ” and “ 2 .” From these signals, the inverse tangent of their ratio similarly produces a linear measure of the angular position, “2 ,” of a magnet (attached to a shaft). Here, the electrical angle goes through two cycles, as angular position of the shaft/magnet traverses one 360-degree revolution. Further information on AMR position sensors is found in [23]. 4)

## Optical Encoder

For a steering-wheel angle sensor application, a slotted-aperture optical-encoder sensor is combined with a gear-reduction-driven potentiometric sensor [24]. The potentiometric sensor provides a continuous measurement of steering-wheel angle over a four-turn lock-to-lock turn range, but with less accuracy than the optical encoder. The encoder, with two offset bands of 90 aperture slots each, is accurate to within 1-degree accuracy, but it can’t determine the absolute position of the steering wheel. Whenever the vehicle starts up, the sensor’s encoder “learns” the true center (or zero) absolute position of the steering wheel by starting with the position indicated by the potentiometer and then refining the calibration based on a period of straight-road driving (as detected by vehicle yaw angular-rate sensors like those described below). 5)

## Magnetostrictive Pulse Transit Time

Magnetostrictive pulse transit-time sensors are used to make long, 200-mm, linear-position measurements. A donut-shaped magnet is attached to and travels with, a displacement-varying element of a suspension strut. A fixed metal rod, concentric to the center axis of a strut, serves as both a magnetostrictive medium and as an acoustic waveguide. A current pulse is applied through the entire length of the rod. When the pulse passes the magnet (attached to the strut), an acoustic pulse is created in the rod due to the interaction of the magnet’s field with the applied current in the magnetostrictive rod (i.e., the direct magnetostrictive effect). An acoustic wave is launched back up the rod. When the wave reaches the top end of the rod, the magnetic permeability of the rod material is modulated by the interaction of the acoustic wave with an applied field of a bias magnet (i.e., the inverse magnetostrictive effect). This permeability change creates a voltage pulse in the sense coil circuit and the measured transit time between initiation of the current pulse and the detection of the return-wave voltage pulse, determines the magnet position (i.e., the displacement of the suspension strut) [25]. Automotive Applications

Because of their mature state of development and low cost; potentiometric sensors are extensively used to measure fuel-float level, accelerator pedal angle, and transmission gear position. Due to the harsh environment of the engine and the high number of lifetime dither cycles, noncontact Hall sensors are used to measure throttle angle, EGR valve position, and wheel-to-chassis height (via a 2-bar, linear-to-rotary displacement linkage). AMR position sensors are used in the same applications as for potentiometric and Hall sensors, however, these are sensors of choice when larger air gaps and/or higher-limit maximum operating temperatures must be accommodated. Hall sensors are also used in seat belt buckles for high-reliability detection of proper buckle engagement8 —i.e., proper linear positions of latch and tongue parts inside the buckle [26]. Because optical sensors can be susceptible to contamination by dirt/oil, they are used in applications that provide environmentally protected mounting locations. A good example is the optical-encoder steering-wheel angle sensor used in vehicle stability enhancement systems, which is mounted on the steering column, near the IP (instrument panel). In active suspension systems, the stroke/position of a strut is accurately measured over an extended-length using magnetostrictive-pulse transit-time sensors. D. Temperature Sensors Temperature sensors have the fourth greatest unit sales and the seventh highest gross sales revenue, which makes them number four in the present categorization scheme. In 1999, in North America, temperature sensors accounted for about 5 % of all automotive sensors sales revenue, with unit sales of 39 million sensors [3], [9]. Temperature sensor technologies, in general use today, are listed below. 1) Silicon IC

Use of single-crystal silicon permits on-chip fabrication of IC (integrated circuit) enhancements. However, the use of IC processes also restricts the operation of siliconbased temperature sensors to an upper limit of about 150 C. Two types of silicon sensors are in general use

(a) spreading resistance based on bulk charge conduction [13] pages 65–70 and (b) pn-junction voltage difference [27]. 2) Thermistor

Ceramic-oxide compositions are manufactured to exhibit NTC or PTC (negative, or positive, temperature coefficient) resistance characteristics, where resistance of the sensors decrease, or increase, several orders of magnitude as temperature is increased [28]. 3) RTD Resistive Temperature Detector

In RTD high-temperature sensors, a platinum-film sensing element is printed and then embedded inside an alumina-ceramic layered structure. The resistance of the platinum element linearly increases as temperature is increased [29]. Automotive Applications

In the temperature range of 50 to 150 C, silicon sensors are used for measurement and control of air, gases and fluids. Thermistor-type sensors operate in various ranges between 55 to 1000 C. Thermistors are used for engine coolant temperature measurement [28] and are also commonly used as level sensors to monitor coolant, fuel, lubricant, brake and steering fluids (where differences between the sensor’s self-heating temperatures when immersed and not immersed, in a fluid provide the output signal). To measure very high temperature, over 1050 C, as required by OBD regulations for catalyst overheat monitoring; both thermistor-type sensor and RTD-type sensors are utilized. To satisfy OBD requirements, these sensors must respond to 0-to-1000 C step changes of temperature within 10 s.

# Other Sensors

## Mass Air Flow

MAF mass air flow sensors are fourth highest in gross sales revenue. On high-performance engines, sensors based on a thermal heat-loss principle, including a hot-wire element (plus a companion compensating hot-wire element), are mounted in a bypass channel of the air intake to measure mass air flow into an engine [30]. This type of sensor measures true mass provided there’s no pulsating reversal of air flow. Under certain operating conditions, pulsating reversal of air flow does occur; in which case, another configuration of the thermal flow sensor is used. This type utilizes a heat source and dual upstream and downstream thermal flow-detection elements (which are fabricated on a micromachined low-thermal-mass diaphragm) [31].

## Exhaust Gas

EGO exhaust gas oxygen sensors have the fifth greatest unit sales and the second highest gross sales revenue. Their high sales revenue reflects the higher costs of oxygen sensors which are about three times higher per sensor than, for example, rotational motion sensors. For use in closed-loop three-way catalytic-converter emissions control of engines, three types of exhaust gas oxygen sensors are currently utilized.

1. Exhaust gas-heated ZrO (zirconium-dioxide) solid-electrolyte sensors electrochemically self-generate a voltage output signal which exhibits a step-like transition at the stoichiometric point (which is the chemically correct air-to-fuel mixture ratio)–see [11, pages 208–213] and [32].
2. Electrically heated titanium-dioxide sensors self-generate a resistive output signal which also makes a step transition at the stoichiometric ratio [33].
3. Electrically heated, planar, low-thermal-mass, ZrO sensors feature fast light off–i.e., they become operational within 5 to 10 s from the ignition-on time of engine start-up [34], [35]. For use in lean A/F airfuel ratio control of engine emissions, two additional types of exhaust gas sensors are utilized.
4. Electrically heated, low-thermal-mass, planar, dual-chamber ZrO sensors utilize oxygen-pump electrochemical-titration operating principles to measure A/F-ratio over a wide range [34]. v) Dual-chamber ZrO sensors, similar to the wide-A/F sensor of (iv), but where the first chamber removes (pumps out) exhaust oxygen, leaving NOx (oxides of nitrogen) and the second chamber dissociates NOx into N and O . In this sensor, the amount of electrochemical pump current in the second chamber is indicative of the exhaust-gas NOx concentration [36].

## Engine Knock

To obtain maximum power, high-performance engines are run at their borderline limit of incipient knock. This is done using closed-loop control of spark timing based on knock sensor feedback. Cylinder-head vibrations in the frequency range of 4-to-8 kHz, excited by engine knock, are detected using broadband-resonant vibration sensors mounted on the engine cylinder-head. Vibration/knock sensors consist of piezoelectric sensing elements in spring-mass sensor packages [37].

## Linear Acceleration

Linear-acceleration inertial sensors have the sixth greatest unit sales and the fifth highest gross sales revenue. Acceleration sensors are used as inputs for chassis applications such as adaptive suspension, vehicle stability and ABS braking systems; as well as inputs for body-systems frontal, side and rollover crash-sensing applications. Reference [38] gives an excellent review of all types of micromachined inertial sensors, including automotive micromachined-based MEMS accelerometers. Three main types of automotive acceleration sensors employ MEMS technology, they are

1. piezoresistive MEMS sensors which incorporate silicon piezoresistors in suspension beams to detect the acceleration- induced movement of a micromachined proof mass [38, pages 1641–1642];
2. capacitive MEMS sensors which incorporate micromachined electrodes to both sense and detect the acceleration- induced movement of a micro-beam (or plate) proof masses [38, pages 1642–1644];
3. resonant-beam MEMS sensors which utilize the principle that a vibrating member will shift its resonant frequency proportional to the (inertial) force exerted on the member [38, page 1644] and [39]. The above MEMS types of acceleration sensors include features such as instrumentation-grade performance at traditional- sensor low cost, robustness, electronically selectable output scales, self testability/diagnostics, on-chip signal conditioning, and multiplex/bus network connectivity. In some chassis applications, however, due to the harsh operating environment; traditional types of accelerometers continue in use today. These are capacitive-type sensors, where acceleration- induced movement of an electromachined thin-metal proof mass (packaged in a ceramic body) is sensed. The sensors feature integrally packaged custom IC circuits which provide binary, high-level, pulse-width-modulated, output signals [40].

## Angular Rate

Angular-rate inertial sensors have the seventh greatest unit sales. Angular-rate sensors are used as inputs for chassis suspension (vehicle roll and pitch) and for vehicle stability (yaw); as well as inputs for body rollover-crash-sensing (roll) and for vehicle-heading navigation applications (yaw). Similar to acceleration sensors, automotive angular-rate sensors also utilize MEMS technologies, 10 and their operation is based on detection of the effects of Coriolis forces acting on different types of vibrating mechanisms such as rings, tines, disks, or plates.

1. The vibrating-ring type of sensor incorporates a polysilicon suspended ring, where either electrostatic and magnetic fields have both been used to excite vibrations in the ring. Either by capacitive or electromotive means (both approaches are presently employed), electrodes detect the effects of the Coriolis angular-rate force on the nodes and anti-nodes in the ring’s vibration pattern with respect to the sensor’s base [38, pages 1651–1652] and [41].
2. The vibrating-tine sensor consists of a tuning-fork-like tines, supported by a cantilever-like stem. The tines are piezoelectrically driven into resonant vibration and piezoresistive sense elements in the stem detect torsional strain resulting from Coriolis angular-rate forces [42].
3. Vibrating-plate and disk, sensors are electrostatically driven/oscillated by comb electrodes, where Coriolis- force-induced lateral displacements of the plate, or the tilt of the disk, are capacitively detected [38, pages 1648–1651] and [43], [44]. Another important automotive type of vibrating-tine angular- rate sensor is made using discrete electromechanical construction [not the MEMS construction of sensor type (ii) above]. This sensor is made from electro-formed quartz, with vibrating tines ten times larger than the MEMS type sensor (10 mm tine length versus 1 mm in MEMS). In this sensor, drive tines are piezoelectrically excited and piezoelectric elements in a second set of pickup tines detect out-of-plane vibrations (resulting from the Coriolis force). Although larger than MEMS sensors, this type of sensor has a large share of the automotive market because of its ruggedness and high performance [45].

## Solar, Twilight and Glare Optical Detectors

Two types of optical detectors are commonly used

* solar-heat-detecting photodiodes which respond to near infrared wavelengths and
* twilight-detecting photodiodes which respond to visible wavelengths [46].

Solar and twilight sensors are typically mounted atop the IP in automobiles. Solar sensors provide input signals for automatic temperature control systems, whereas twilight sensors are used to automatically turn on headlights. A third application of optical detectors utilizes photosensitive microchips that detect visible-light/glare and which are used in automatic- dimming rearview mirrors [47].

## Moisture/Rain

These sensors are usually mounted facing the windshield, behind the rearview mirror. Typically, moisture-detecting sensors emit IR (infrared) light beams through the windshield. When rain droplets impinge on the outside of the windshield, a higher refractive-index rain/liquid layer is created. Depending on design (i.e., the angle of IR beam incidence on the glass), the presence of rain on the windshield makes IR light either refract away more, or reflect back more [48]. These sensors provide feedback signals for automatic windshield wiper control.

## Fuel Level

Although other technologies have been developed—e.g., optical, ultrasonic and capacitive—the potentiometer float-arm technology for fuel-level measurement prevails because of its low cost, high reliability and durability [49]. Thick-film resistive tracks are generally used in the potentiometer. The float is designed to traverse a path near the tank’s center for all fuel levels. An appropriate functional relationship between sensor angle and fuel quantity for the particular tank shape used in each vehicle is used. A running average of fuel sensor output signals is utilized to compensate for fuel slosh created due to vehicle motion.

## Near-Distance Obstacle Detection

Several technologies exist–namely ultrasound, microwave radar, rf capacitance and infrared multi beams; all are primarily used in reversing-aid systems (“blind spot” monitoring systems have not yet reached production status). The ultrasound technology is used in widespread production because it offers wide-area, near-distance beam coverage and is low cost [50]. On the other hand, wide-beamwidth microwave radar, although more costly, offers advantages of greater range, better accuracy and ability to operate in inclement weather. Ultrasound obstacle detection is currently in production in reversing-aid systems on (obscured- rear-vision) minivan and SUV types of vehicles. Radar types of obstacle reversing-aid detection are in production on certain commercial vehicles, partly due to legislation in some U.S. states that requires this feature for trucks. Hybrid systems, which combine ultrasound (for wide-area close-proximity obstacle detection) with wide-beamwidth radar (for extended-range, better accuracy, all-weather detection), are expected to appear soon in production [51].

## Far-Distance Obstacle Detection

Four main technologies are used–namely millimeter-wave radar, laser radar, IR thermal imaging, and machine vision. Millimeter-wave and laser radar are used primarily in vehicle ACC adaptive cruise control systems (which control both speed and vehicle-to-vehicle spacing, rather than speed alone).

1. Millimeter-wave radar operates at specified government- regulated frequencies ranging between 24.7 GHz to 77 GHz and it features the ability to accurately operate in inclement weather. Some radars use FM/CW frequency-modulated/continuous-wave signals which allow measurement of range and range rate11 of as many as 20 targets (including vehicles, roadway obstacles, etc.). Other automotive radars use pulsed-dopplar and/or monopulse operating principles. Most radars utilize some form of beam scanning, with 10-Hz repetition (update) sweep rates, to resolve, for example, whether targets are in the same roadway lane, an adjacent lane, or an oncoming lane. Some radars utilize all-electronic (no moving parts) beam scanning [52], [53]. Other radars utilize mechanically driven beam scanning [54]. Heavy-truck radars often use nonscanning, single-lane coverage, fixed beams [55].
2. Laser radar, or lidar (acronym derived from light radar), emits narrow, pulsed, IR beams at wavelengths in the vicinity of 850 nm. Short-duration 25-ns pulses are emitted sequentially over wide range of beam-scan (both horizontal and vertical) directions. Transit times of individual pulses determine distances to reflecting targets. Beam scanning on automotive lidars is generally accomplished using electromechanically driven mirror-scan mechanisms [56], [57]. Laser radar performance is diminished by inclement weather and/or dirty lenses (actually, this limitation is promoted as a safety benefit because it limits the use of ACC in poor weather when driver visibility is also limited). On the other hand, laser radar features high accuracy, wide angular coverage and precise target location.12 13
3. Passive IR, nonradiating, thermal imaging, night vision is available on production automobiles [61]. Development of two-dimensional, micromachined, IR bolometric focal-plane arrays [62] was the key technical breakthrough most responsible for night vision becoming low cost enough for automotive application. For automotive night vision, a typical focal-plane array consists of 240 lines, each 320 pixels wide, giving a total of 76 800 pixel image elements. When infrared thermal energy (from pedestrians, deer, other cars, etc.) is incident on the array, each pixels alters its capacitance, which is electronically monitored and input to a heads-up, real-time, small video display of a virtual image viewed by the driver above the hood of the vehicle [61].
4. Machine vision is used to monitor a vehicle’s position relative to roadway lane markings. When, for example, a truck begins to stray outside its lane (possibly indicating a drowsy driver problem), an audible lane-departure “rumble strip” sound is sent to the speaker on whichever side of the roadway the truck is departing [63]. The vision sensor consists of a) a digital camera, with typically 100 000 pixels and 120-dB dynamic range, mounted on the windshield inside the truck cab; and b) advanced image-recognition software that incorporate lane-recognition/vehicle trajectory algorithms.

## Additional Production Sensors

Additional automotive sensors are in volume production, but are not covered in the above paper. These sensors include

1. short-circuit-ring position sensor used in electronically controlled diesel injection pumps;
2. finger-type angular-position and angular-speed sensor;
3. oil level/quality sensor using heated wires to detect change in heat conductivity due to oil aging.

# Emerging sensor technologies

Emerging, state-of the-art, sensor technologies are defined here as those which are currently in the R&D stage of development, or those which have been newly introduced and which are expected to have a significant impact on automotive systems development.

## Engine Combustion Sensors

### Spark Plug Ion-Current (Using Either dc or ac Applied gap Voltage)

Detects misfire and detonation/knock; and also indicates in-cylinder peak pressure and air-fuel ratio [64], [65].

### Fiber-Optic Diaphragm-Reflection

Detects in-cylinder pressure waveform [66], [67].

### Piezoresistive Silicon-Carbide-On-Insulator

Detects in-cylinder pressure waveform [68].

## Oil Quality/Deterioration Sensing

### Stress-Based Predictive Method

Cumulative stress on oil is calculated from combined effects of engine revolutions and oil temperature [69].

### Multisensor

Detects oil dielectric constant and oil level (capacitively), plus oil temperature [70].

## Engine/Transmission/Steering Torque Sensors

### Twist-Angle Torsion-Bar

Twist angle due to applied torque is detected potentiometrically (using sliding contacts [71], [72]); and also via the following noncontact methods

* optically, using variable apertures [73];
* optically, using displaceable bar codes [74];
* magnetically, using displaceable air gaps [75];
* electrically, using eddy current with variable shaded poles [76].

### Non-Torsion-Shaft Magnetoelastic Detection

In one sensor, ac-excitation is used to detect changes in shaft permeability [77]. In the other type, permanently magnetized shafts or sleeves self-generate a dc-magnetic flux signal [78], [79]. Both sensors operate without contacting the rotating shaft. 3) Engine-Crankshaft Speed Variation Due to Cylinder-Firings Math algorithms are used to derive the engine torque from measurements of engine-flywheel speed modulation due to individual cylinder firings—high-resolution rotational motion sensors are utilized [80].

## Multi-Axis Micromachined Inertial Sensors

1) Two-Axis Accelerometer/Tilt

Single-chip micromachined two-axis ( - , lateral-longitudinal, vehicle axes) dual-function, sensors are used for vehicle-security systems (e.g., towaway tilt detection) [81], [82].

2) Combined Angular-Rate/Acceleration

Micromachined combined-function sensors are fabricated on the same substrate, providing in one package dual independent measurements of lateral vehicle acceleration and yaw angular rate for use in chassis systems for input to vehicle stability systems and for body systems for rollover-crash-sensing [83]. This sensor is in major production in Europe.

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